BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: The Application of In-Flight Winds to the Design and Operation of the Saturn V/Apollo Vehicle
Case 340

DATE: September 11, 1967

FROM: W.W. Elam

ABSTRACT

This memorandum was prepared in response to a request by STAC for a description of in-flight wind models used in launch vehicle specifications and operations.

The Saturn V vehicle is affected both by strong steady winds and the changes of wind speed with altitude particularly if these changes can excite resonant responses in the vehicle structure. The data base is adequate only for large scale wind features (quasi-steady-state winds). New measuring techniques have had to be developed to measure the small scale changes with altitude which are of interest. The limited amount of data available on the small scale features (about 20 months) shows the design values established in 1962 to be very moderately conservative.

Although the design wind profile is based on a 95 percentile wind for the windiest month (March), it is expected that operational launch capability will be restricted on the average somewhat less than 5% of the time in the windiest month (March).

A brief description is given of the features of the wind field which adversely affect spacecraft launch operations including discussion of the jet stream and small scale motions including clear air turbulence (CAT).

It is concluded that the considerations of in-flight winds in the design and operation of the Apollo vehicle is satisfactory.

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MEMORANDUM FOR FILE

The Saturn V/Apollo Vehicle

The maximum effect of in-flight winds on the vehicle is in the altitude region of maximum dynamic pressure. This occurs at an altitude of about 11 km. This also is the altitude region where the strongest winds are found at KSC. The vertical velocity of the vehicle is about 400 m/s at this altitude.

The vehicle is affected by strong steady winds in that aerodynamic forces cause the nose of the vehicle to deflect into the wind. This effect must be corrected by gimballing the engines to keep the angle of attack within acceptable limits to avoid overstressing the vehicle. The vehicle is also sensitive to changes of wind speed in the vertical - because of the magnitude of the shear but particularly if the wave length of the wind speed change with altitude can excite resonant responses in the vehicle. The most important of such responses are (wavelengths given are approximate):

First bending mode	--Responds to wavelengths of 400 m
Second bending mode	--Responds to wavelengths of 200 m
Control mode	--Responds to wavelengths of 2000 m
Fuel sloshing	--Responds to wavelengths of 2000 m

In summary the features of the in-flight winds to which the vehicle is particularly responsive in the maximum dynamic pressure region are strong winds and shears and variations in wind profile with wavelengths of approximately 200 m, 400 m, and 2000 m.

Wind Measuring Techniques

The primary source for the in-flight wind data are observations taken by the conventional GMD system (Ground Meteorological Detector). A rising balloon with a suspended radiosonde (transmits temperature, pressure, humidity data) is tracked by a radio direction finder system. Accuracy of the measured wind varies between 2 and 15 m/s. The greatest errors are associated with strong winds, and result from low elevation angles for tracking. The details of the structure of the wind in the vertical with demensions less than 800 m are filtered or smoothed out. The data base consists of 8 years of observations at KSC (two observations per day).

Since the GMD system did not measure the detailed structure required for Apollo other wind measuring systems have been developed and used. The system in use at KSC tracks a roughened spherical superpressure rising balloon (the Jimsphere) with an FPS-16 radar. RMS wind speed error is 0.5 m/s. Vertical structures with dimension of 75 m or greater are measured. Routine observations were commenced in Nov. 1965 at KSC where two observations per day are taken, five days per week. Measurements are also made at the Western Test Range and the White Sands Missile Range.

Also a number of observations have been taken by the technique of photographing a vertical smoke trail. This technique enables the discrimination of fine detail in the vertical wind profile but weather restrictions, cost, data reduction and other considerations make it undesirable for routine scheduled measurements to be made.

Design Wind Criteria

Wind data inputs for space vehicle design purposes are commonly of three types -- sample measured profiles, statistical distributions, and discrete or synthetic profiles. The discrete or synthetic profile is used in Apollo design. This decision was made in 1962-63. It is not the purpose here to discuss that decision but rather to assess how the vehicle so designed is affected by in-flight winds.

The Apollo design wind profile is based on quasi-steady-state wind speeds, wind shears, and gusts. The data are given in the Apollo Program Document -- Natural Environment and Physical Standards for the Apollo Program (NEPSAP) in paragraphs 2.3.2.5, 2.3.2.6., 2.3.2.7., 2.3.2.8., 2.3.2.9. (Reference 1). The construction of the discrete wind profile is briefly as follows.

The 95 percentile quasi-steady-state wind envelope for the strongest wind month (March at KSC) in the 10 to 14 km altitude region is the basic element in constructing the synthetic profile. The wind speeds at any selected altitude are built up to the 95 percentile steady state envelope by applying 85% of the 99 percentile shear values given in paragraph 2.3.2.6. of NEPSAP. This shear build up is joined to a gust which is added to the steady-state profile. The gust added is 85% of a gust of 9 m/s magnitude. This gust factor is built up over an altitude change of 25 m -- a shear of .36 s^{-1}. The "corners" are smoothed by a prescribed method. A more detailed description is given in NASA TM X-53328, a supporting document to NESAP (Ref. 2). (A detailed analysis of the in-flight wind data for KSC is presented in Ref. 2.)

While this synthetic wind profile does not too closely resemble an actual wind profile is good basis for design bacause it contains elements of real wind profiles to which the Saturn/Apollo vehicle is sensitive. It is also simple enough to be used widely as a standard throughout the Apollo community. It does not provide explicitly for repeated excitation of the response modes of the vehicle. Detailed wind profiles measured with the "Jimsphere"/FPS-16 system are used for this purpose.

<u>The Synthetic Profile and the Data Base</u>

The Apollo in-flight design synthetic wind profile was established in its major features in 1962. It is interesting to note the data base which supported the major elements (quasi-steady-state winds, shears, and gusts) at that time. The only reasonably adequate data base was for the steady state winds. These data were the GMD data. Indeed, the differentiation between quasi-steady-state winds and "turbulence" (shears, gusts) was based on the capability of GMD system. The wind features which the GMD could measure were called quasi-steady state winds. The other required wind features which the GMD could not measure were called "turbulence" (shears and gusts), except that shears over altitude differences of 800 m or greater were measured by the GMD system. The data on turbulence were very meager. Data from a few instrumented aircraft flights and a few smoke trail measurements were available. Thus the gust value of 9 m/s and the shear values given in paragraph 2.3.2.6. of NEPSAP for small altitude increments were based on very limited data. The 99 percentile shear values were used because shears could not be accurately measured with the GMD system, and to lower the risk level due to shears during flight through the atmosphere.

As noted above the "Jimsphere"/FPS-16 is the only wind measuring system now in use which will provide the data necessary to build the statistical data bank for the small scale in-flight wind features. Cnly about 20 months of data have now been taken. Based on this limited amount of data we can compare a sample of the 99 percentile shear values so obtained with the values given in NEPSAP. For a 50 m/s wind speed we find ---

Vertical Distance (m)	Shear (sec^{-1})	
	NEPSAP	"Jimsphere"
100	.09	.06
200	.055	.045
400	.0375	.035
600	.0308	.030
1000	.0239	.025

With regard to the 9 m/s gust, the "Jimsphere" has measured gusts of 7-8 m/s at KSC. With regard to the shear used in applying the gust to the quasi-steady-state wind (.36 sec^{-1}), although the "Jimsphere"/FPS-16 system cannot measure the structure over 25 m altitude differences, such shears have been measured on a few occasions by the smoke trail method and by aircraft.

Based on the limited data sample available from the "Jimsphere"/FPS-16 observations it would appear that the "turbulence" wind criteria values set down in 1962 were very moderately conservative. Of course using the 99 percentile shear values introduced another measure of conservatism on the basic 95 percentile capability.

Thus we can say that based on the in-flight wind design criteria established in 1962 and considering the limited amount of detailed wind data taken since Nov. 1965, that the Saturn V/Apollo operational launch capability will be restricted by in-flight wind conditions on the average less than 5 percent of the time in the windiest month (March), somewhat less in Jan., Feb., and April and significantly less in other months. However, it should be noted that the real capability of the vehicle as manufactured to withstand the effects of in-flight winds may be more pertinent.

Characteristics of Atmospheric Motion in the Strong Wind Altitude Region

Much has been revealed about the nature of motions in this region (the Jet Stream) by the Jimsphere/FPS-16 wind measuring system and special aircraft flights. The vertical wave length of motion as it has been used here is defined as the altitude interval between successive wind speed maxima or minima. The amplitude of the vertical vave is defined as being equal to half the difference between "the average of two wind speed minima" and "the included maximum".

Characteristics of detailed wind speed observations show that the wind speed perturbations can be divided into three categories:

1. Type 1 consists of perturbations having vertical wavelengths usually greater than 5 km and amplitudes greater than 20 m/s. They can be identified for long periods of time. This perturbation is what is commonly referred to as the jet stream. The attached depiction of a vertical cross section across a typical jet stream shows the gross features of the change of wind speed with altitude and latitude (see Figure 1, CROSS SECTION OF JET STREAM);

2. Type 2 consists of perturbations having a vertical wavelength of 200 m to 2000 m and amplitudes of 1 to 20 m/s. These features are identifiable for periods longer than 6 hours although both wavelength and amplitude vary with time;

3. Type 3 consists of perturbations having vertical wavelengths less than 500 m and amplitudes less than 3 m/s. These motions are turbulent. The motions in the eddies having wavelength less than 300 m are nearly isotropic. The vertical component of the motion relative to the horizontal components decreases as the size of the eddy increases above 300 m.

Motions having vertical wavelengths 200 m to 500 m are found both in categories 2 and 3. Type 3 is characterized by isotropic motion. Type 2 is characterized by thin layers of large horizontal extent which are stable and move relative to each other without appreciable interchange. The resulting vertical shears appreciably affect the Saturn vehicle.

Clear air turbulence (CAT) which is of concern to aircraft operations is essentially motion of type 3 with the aircraft being affected by the vertical component of the motion. CAT wavelengths range from 50 m to 500 m. The vertical component of the motion is of little concern to spacecraft launches.

A combination of physical causes can produce the observed small scale motions of types 2 and 3. There is commonly a structure of temperature stratification, sometimes intense, at the tropopause jetstream altitudes. In such a stably stratified atmosphere strong wind shears, small gravity waves, and shear waves can develop and propagate. Inertial effects can cause intensification or diminishing of the shears. A number of effects modify the small scale temperature structure such that the shears and wave motions become unstable. One form of dissipation of the energy is into shorter wavelength turbulence.

Operational Capability of the Saturn/Apollo (with respect to in-flight winds)

Although the vehicle design was based on a discrete or synthetic wind profile, its response to real wind profiles (Jimsphere/FPS-16) has been calculated using an analogue computer, with checks made on a digital computer. The analogue method is said to be accurate to within 5%. Calculations made on about one year of data (400 wind soundings) show the vehicle to have a 99 plus percent capability, or a 99% capability in March. More importantly perhaps, these calculations show the effects due to shear and gusts (effects other than that due to the quasi-steady-state winds) to be in nearly the same relative amount as the shear and gust effects calculated using the design synthetic wind profile.

It would be quite premature to say that the vehicle will have a 99 percent in-flight wind capability in a future strong wind month. Its response is strongly dependent upon the payload carried. Also, the year to year variations in the quasi-steady-state wind speeds are quite marked. This is shown by the following: a list of the number of wind soundings where the wind speed was greater than 50 m/s during the month of March for the years 1956 1961. (Total number of observations per month is 62.)

Year	Number of Observations with Winds Greater than 50 m/s
1956	31 of 62
1957	35 of 62
1958	52 of 62
1959	52 of 62
1960	46 of 62
1961	24 of 62

The strong in-flight winds affecting KSC are usually associated with the subtropical jet stream. There is a strong gradient of wind speeds across a jet stream (see Figure 1) and consequently the year to year or week to week small variations in the location of the jet stream are reflected in large variations in wind speeds at a particular geographic location.

Thus it can be said that the incidence of quasi-steady-state winds of greater magnitude than the 95 percentile design quasi-steady-state wind may be greater (or less) than 5 percent in March of 1968, 1969, 1970. However, the operational restriction due to high speed in-flight winds can be diminished by the use of a bias tilt program in the vehicle. Briefly, a bias tilt program causes a trajectory such that the vehicle in passing through the 10 - 14 km high wind altitude region has a horizontal velocity vector in the direction of the horizontal velocity vector of the wind which results in a decrease in the relative wind acting on the vehicle.

However, the effects of the small scale structure of the wind cannot be so alleviated. The calculations of vehicle response to actual detailed ("Jimsphere" /FPS-16) wind soundings have shown that the vehicle (at the 90 m station) can be over-stressed even though the quasi-steady-state wind speeds are low, well below the design wind speed. The forward vehicle stations are relatively much more affected by the turbulent (shears and gusts) features of the detailed wind profile than are the after stations.

Forecasting In-Flight Winds for Operational Purposes

The planning for Apollo operations does not allow for a forecast of in-flight wind conditions of longer than 6 hours duration to affect the prelaunch operations. This planning is considered valid. Assume that an actual vehicle has a 98 percent in-flight wind capability for the period of the launch. Notwithstanding skill demonstrated in forecasting many meteorological elements, it is not believed that sufficient skill can be demonstrated to affect important operational decisions when the forecast requirement is to differentiate accurately between an event that occurs one percent of the time and one that occurs three percent of the time. Consequently, it would be impractical to base important operational decisions upon such forecasts if it could be avoided.

Rather than a forecast, a system of close monitoring of the detailed in-flight winds by repeated observations and a means to calculate rapidly in detail the effects of the wind on the vehicle, as is presently done, is the proper approach.

Conclusion

At the present time the consideration of in-flight winds in the design and operation of the Apollo vehicle is satisfactory.

W. W. Elam

W.W. Elam

1011-WWE-map

Attachment
Figure 1

REFERENCES

(1) Apollo Program Document M-DE8020.008B (SE 015-001-1) Natural Environment and Physical Standards for the Apollo Program.

(2) NASA TM X-53328, Terrestrial Environment (climatic) Criteria Guidelines for Use in Space Vehicle Development, 1966 Revision.

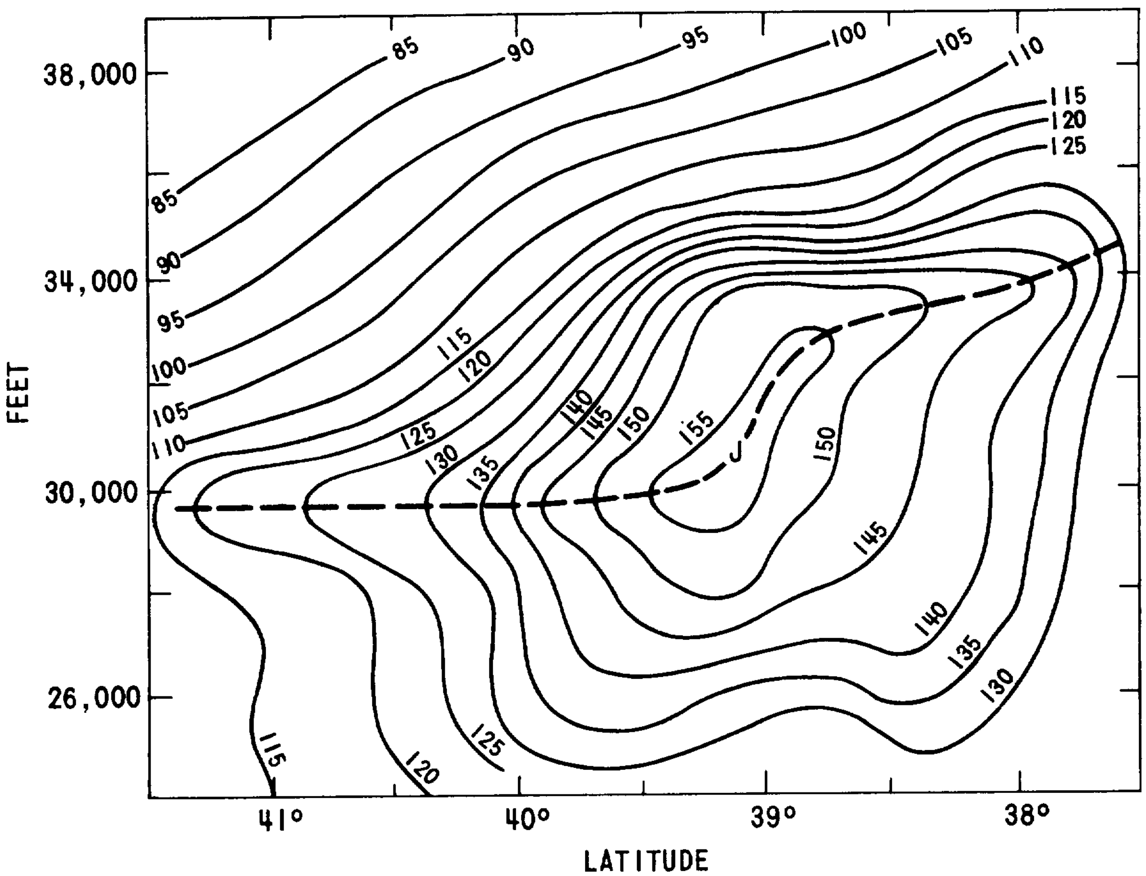

FIGURE 1 - CROSS SECTION OF JET STREAM. SOLID LINES ARE ISOTACHS OF THE WIND FIELD (KNOTS). THE HEAVY DASHED LINE MARKS THE POSITION OF THE JET CORE. (FROM JOURNAL OF THE ATMOSPHERIC SCIENCES, SEPT. 1964)

BELLCOMM, INC.

Subject: The Application of In-Flight Winds to the Design and Operation of the Saturn V/Apollo Vehicle

Date:

From: W.W. Elam

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TO: MA-2/Technical Manager, Systems Engineering Support

FROM: Mr. B. F. Brown, Bellcomm, Inc.

X67-37774

TITLE OF REPORT "The Applications of In-Flight Winds to the Design and Operation of the Saturn V/Apollo Vehicle"

AUTHOR(S) W. W. Elam

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X67-71532

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